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OBSERVATION OF IMPULSIVE ACOUSTIC EVENTS AND THE EXCITATION OF SOLAR OSCILLATIONS

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OBSERVATION OF IMPULSIVE ACOUSTIC EVENTS
AND THE EXCITATION OF SOLAR OSCILLATIONS

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ABSTRACT

The five minute solar oscillation has been exploited in numerous seismic studies in which internal properties of the Sun have been inferred. It is generally regarded that these modes are excited by turbulent convection in the Sun's outermost layers. We observe the oscillatory wakes caused by impulsive events, matching those described by Lamb (1909). These correspond to the events modelled by Goode, et al. which they associate with excitation of the global five minute oscillations.

Subject Headings: Sun: oscillations - Sun: atmospheric motions - Sun: atmosphere

1. Introduction

During the 1960's, many thought that the five minute oscillation is a locally excited impulsive near-surface event arising from decelerating granules, see the review by Noyes (1967). Stein & Leibacher (1974) reviewed several attempts to describe the five minute oscillation by the response of a stratified atmosphere to specific idealized excitations, first offered by Lamb (1909). The germane result from Lamb (1909) is that, after an impulse, the resulting acoustic front propagates through the atmosphere at the local speed of sound followed by its wake in which the vertical phase velocity quickly becomes very large and the frequency approaches the acoustic cutoff. Throughout this paper, the word "event" will be associated with occurrences analogous to those that were idealized by Lamb (1909). Such events would be characterized by a large and time-dependent vertical phase change through the photosphere, and by an associated acoustic flux. The vertical phase gradient starts out with a positive value, swings through zero to a negative value and returns to zero. That vertical phase gradient gives rise to upward flux in the early part of the event and a gradually fading downward flux later.

The now standard explanation of the five minute oscillations, as a beat phenomenon of sound waves trapped inside the Sun, was considered as one possibility in the comprehensive review of Stein & Leibacher (1974). That explanation was observationally confirmed by Deubner (1975). The trapped waves are evanescent in the photosphere, and therefore exhibit only a small vertical phase change through the photosphere due to dissipation. Stein & Leibacher (1974) argued that events matching Lamb's description belonged to a higher frequency range and had no appreciable power. They further argued that the early observers had focused on the small spatial (i.e., horizontal) scale properties of the oscillations and had missed their global nature which only becomes apparent on larger spatial scales. With this understanding of the nature of the modes the seismic potential of the oscillations began to be realized. See Gough and Toomre (1991) for an up to date review of the impressive and solid results from helioseismology. Our understanding of the excitation of these oscillations is more problematic.

Most believe the arguments of Goldreich & Keeley (1977) and Goldreich & Kumar (1988) that the five minute oscillations are stochastically excited by turbulent convection just beneath the photosphere in the region of maximal convective velocities. However, there are some quantitative problems. In particular, this mechanism seems to describe the excitation of low degree oscillations (l <100), but it predicts too great an amplitude for higher degree oscillations (Libbrecht et al. 1986). Brown (1991) infers that since the stochastic excitation occurs as a high power of the convective velocity in the aforementioned picture, the most significant part of the excitation occurs where the convective velocities significantly exceed their mean. Thus, the excitations should be temporally and spatially quite isolated. This being the case, Brown (1991) suggests how one might design an appropriate observing programs to detect these events. Brown et al. (1992) have looked for such events by studying frequencies above the acoustic cutoff.

Stebbins & Goode (1987) observed the solar velocity field at several altitudes in the photosphere using very small steps in space and time. After filtering their data to pass the power from the five minute region of the $k - \omega$ diagram, they averaged the velocity amplitude and phase information over space and time. They found that the mechanical motions had a phase behavior as though they were sometimes travelling up and sometimes travelling down, with low amplitude motion tending to show the largest phase changes. On the face of it, this sounds more like the acoustic events in Noyes (1967, cf. fig. 2) than the beat phenomenon described by Stein & Leibacher (1974). Goode, Gough & Kosovichev (1992) showed that the velocity amplitude and phase behavior of the averaged data of Stebbins & Goode (1987) is consistent with impulsive events occurring less than 200 km beneath the photosphere. Each impulsive event has a resulting wake that has a five minute period component. In the one dimensional calculations of the expansive events by Goode, et al. (1992), there are acoustic fronts and wakes which pass through the photosphere and are partially reflected as they traverse the photosphere. This reflection and the progression of the frequency toward the acoustic cutoff causes the apparent downgoing motion. Goode, et al. (1992) suggested that some of what Stebbins & Goode (1987) have seen is the residue of the excitation of the five minute oscillation presumably arising from convective overshooting. In their calculations, much of the energy from the events propagates downward into the Sun's interior presumably to emerge in different places as the standing five minute oscillation. The argument of Goode, et al. (1992) would be much strengthened if the chronology of events seen by Stebbins & Goode (1987) were consistent with the calculations.

A new reduction of the Stebbins & Goode (1987) data reveals a chronology of individual events which is consistent with the impulsive event picture for the excitation of the five minute oscillation.

2. The Data

For the purposes of this paper, the observations and the reduction of the data will only be summarized; the method is described in detail by Stebbins & Goode (1987). The original data consists of CCD images taken with the Echelle Spectrograph on the Vacuum Tower Telescope at the National Solar Observatory in Sunspot, New Mexico. The images are arranged to show the line profiles of Fe I 543.4 nm at 100 adjacent locations on the spectrograph slit, 0.64 arc sec apart. This particular line was chosen because it is the highest-lying, non-magnetic line in the visible solar spectrum (Altrock et al. 1975), thereby yielding the most altitude information with the least sensitivity to magnetic effects. The line core is formed just above the temperature minimum. A CCD image was acquired every 8.67 s for 37 min. Twenty-five such data sets taken between 31 October and 4 November 1981.

The reduction commences with the determination of nine velocities at nine depths in each line profile. See Stebbins & Goode (1987) for an indepth discussion of the definition of several velocity-like signals from a single line profile. Although the altitude associated with these velocities and their mutual independence are open to some discussion, we take as given that they span the photosphere, that velocities derived from progressively greater line depths reflect progressively greater altitudes in the photosphere and that overlapping contribution functions only reduce altitude dependent variations.

We then proceed to transform the velocities at each altitude from the space-time domain to the temporal-spatial frequency domain for filtering. To pass only the region of

$k - \omega$ space occupied by the five minute oscillations, temporal frequencies are bandpassed and spatial frequencies are low-passed. The velocities are then returned to the time domain, but in the form of the analytic signal with the aid of the Hilbert transform. The Hilbert transform of a time domain signal is the original signal with all frequencies phase-shifted 90^0. The analytic signal is a complex function with the original signal in the real part and its quadrature signal (i.e. Hilbert transform) in the imaginary part. This rectangular representation of a complex function of altitude z, horizontal (slit) position x and time t, of course, has a circular counterpart with an amplitude $A(x, z, t)$ and generalized phase $\Phi(x, z, t)$. This representation is sometimes referred to as the modulation domain.

The amplitudes and phases from this reduction can be presented several ways. Stebbins & Goode (1987) studied eigenfunctions made by forming amplitude ratios and phase differences between altitudes. They also calculated the kinetic energy flux versus altitude averaged over all the data. For this paper, we have additionally calculated the vertical phase gradient and the acoustic flux at each point in the position-altitude-time grid, and then computed temporal auto- and crosscorrelations of these variables to show the relative chronologies.

We adopt here a useful operational definition of the mechanical flux-- the standard one used by the observers. This mechanical flux is defined by the product of the kinetic energy density and the group velocity,

$$u = \rho V^2 v_g, \tag{1}$$

where ρ is the local density, V is velocity amplitude of the oscillation and v_g is the group velocity. In the part of the $k - \omega$ diagram of interest to us,

$$v_g \approx \frac{c^2}{v_{ph}} \tag{2}$$

where the phase velocity is given by

$$v_{ph} = \frac{\omega}{k_z}, \tag{3}$$

and k_z is the vertical wavenumber which we can determine from the observed phase differences with altitude. In detail, we have

$$k_z = \frac{\Delta\phi}{\Delta z}. \tag{4}$$

3. Chronology of Acoustic Events

When we examine the time evolution of velocity events, particularly their associated vertical phase gradient and acoustic flux, we see a range of behaviors of these variables. Most commonly, the velocity amplitude increases throughout the photosphere and over a limited horizontal extent, an upward flux plume reaches up from the bottom to the middle of the photosphere and fades, and as the velocity amplitude recedes, a downward flux plume forms and recedes. To characterize the average chronology of these events, we have calculated the autocorrelation of the flux and the crosscorrelation of the velocity amplitude and the flux with time at every spatial position and averaged them.

The presence of a downward flux following an upward flux can be seen, in an average sense, in the autocorrelation of the flux (Fig. 1). An anticorrelation can be seen at a lag of 6.1 min. This is the delay by which the downward flux plume follows the upward flux plume.

The temporal relationship of these flux plumes to the velocity amplitude can be seen in their crosscorrelation (Fig. 2). The upward flux plume leads the peak of the velocity amplitude by 1.3 min. and the downward plume follows it by 5.0 min.

The autocorrelation of the acoustic flux calculated from the model of Goode et al. shows an anticorrelation corresponding to that in Figure 1 at a lag of 4.2 min. Following them, we have chosen the model (shown in their Figure 1.b) which best fits the time-averaged results of Stebbins & Goode (1987), that is with the impulsive force acting 100 km beneath the photosphere with a half-period of 200 s. The crosscorrelation of the velocity amplitude and flux is shown in Figure 3. The upward flux in Figure 3 leads the amplitude maximum by 1.6 min. and the downward flux follows by 3.9 min. Presumably, the impulses underlying Lamb events in the photosphere have a range of half-periods. With a half-period of 300 s, the model gives an anticorrelation in the autocorrelation at a lag of 5.9 min., an upward flux leading amplitude by 3.0 min. and a downward flux following amplitude by 4.3 min. A model with a half-period of 150 s gives an anticorrelation in the autocorrelation at a lag of 4.3 min., an upward flux leading amplitude by 1.4 min. and a downward flux following amplitude by 4.0 min. These results are in good agreement with Figure 2.

4. Discussion

Lamb events are caused by an impulsive force acting just beneath the photosphere, and consist of a pressure front followed by an oscillatory wake with rapidly time-varying vertical phase gradient and a frequency increasing to the acoustic cutoff. We have seen that the chronology of the acoustic events in the data of Stebbins & Goode (1987) closely mimics the behavior of idealized Lamb events. Specifically, we have shown the presence of upward flux before the maximum in the velocity amplitude and downward flux after the maximum.

The standard picture of the coherence patches of the five minute oscillations predicts that the waves are evanescent, except for a constant, and relatively small, vertical phase gradient due to dissipation. Hence, the coherence patch picture does not predict the large positive and negative phase shifts reported in Stebbins & Goode (1987), and large upward and downward fluxes reported here.

These results show that Lamb events are present, and hence support the contention of Goode et al. that they may play a significant role in the excitation of the normal modes of the Sun. The events discussed here occur much more frequently than those surmised by Brown (1991). However, it could be that more massive events contributing significantly more to the excitation of the five minute oscillation remain to be observed.

Currently, we are analyzing new data taken to further study the connection between the acoustic events reported here and the global five minute oscillation. We have made similar observations, but now with 256 spatial points 4 arc sec. apart and the duration of each dataset is about six hours rather than being less than one hour. With the greater spatial coverage, we are much more likely to detect, if they occur, the events postulated by Brown (1991). With the longer time series, we hope to deduce an energy budget and to separate the Lamb events from the coherence patches.

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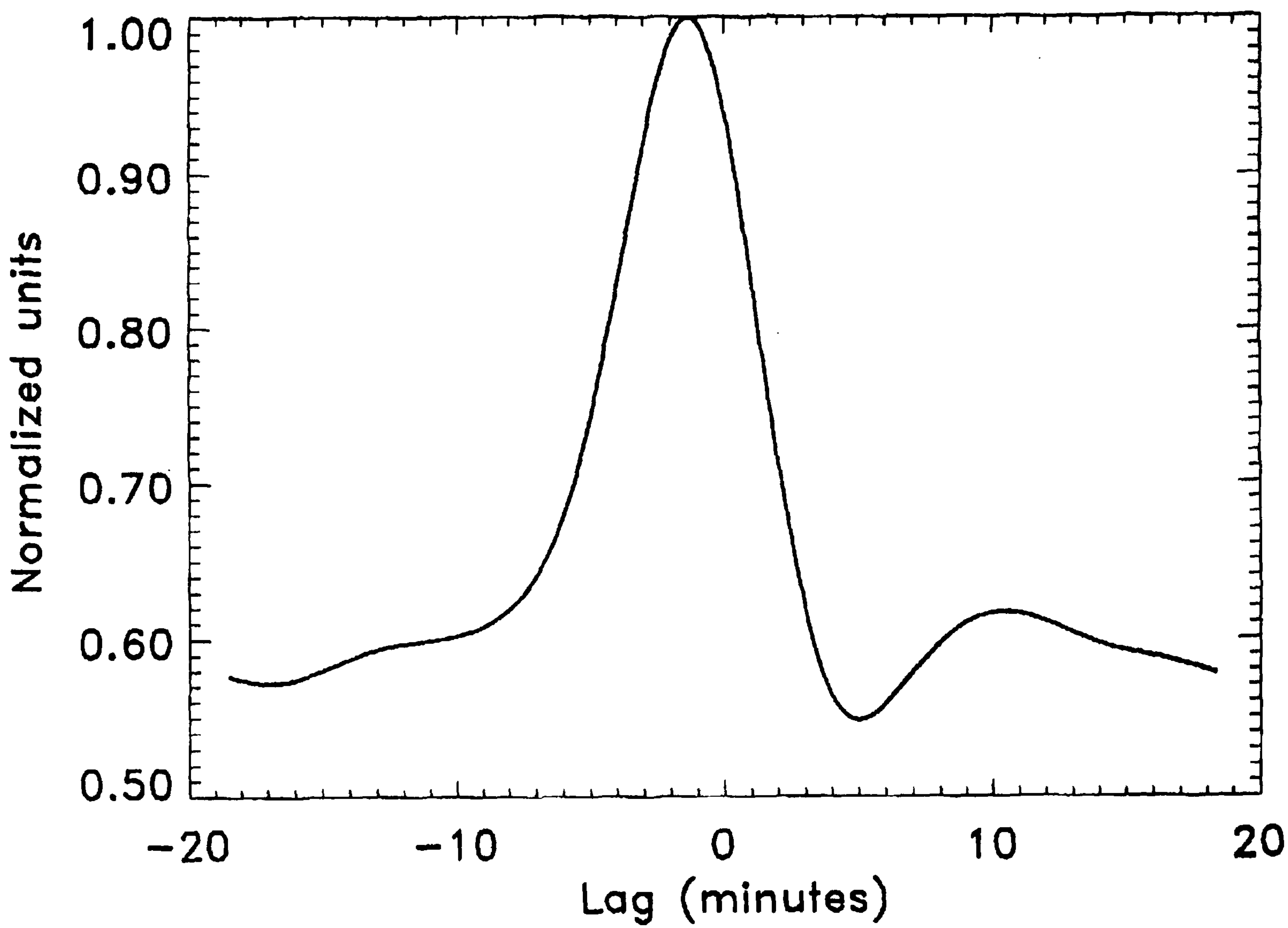
Figure Legends

Figure 1. The temporal crosscorrelation of velocity amplitudes and fluxes from Stebbins & Goode (1987).

Figure 2. The temporal autocorrelation of fluxes from Stebbins & Goode (1987).

Figure 3. The temporal crosscorrelation of velocity amplitudes and fluxes from Goode et al. (1992).

Data


1.00
0.90
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0.60
0.50
Normalized units
−20
−10
0
10
20
Lag (minutes)

Fig 1

Data

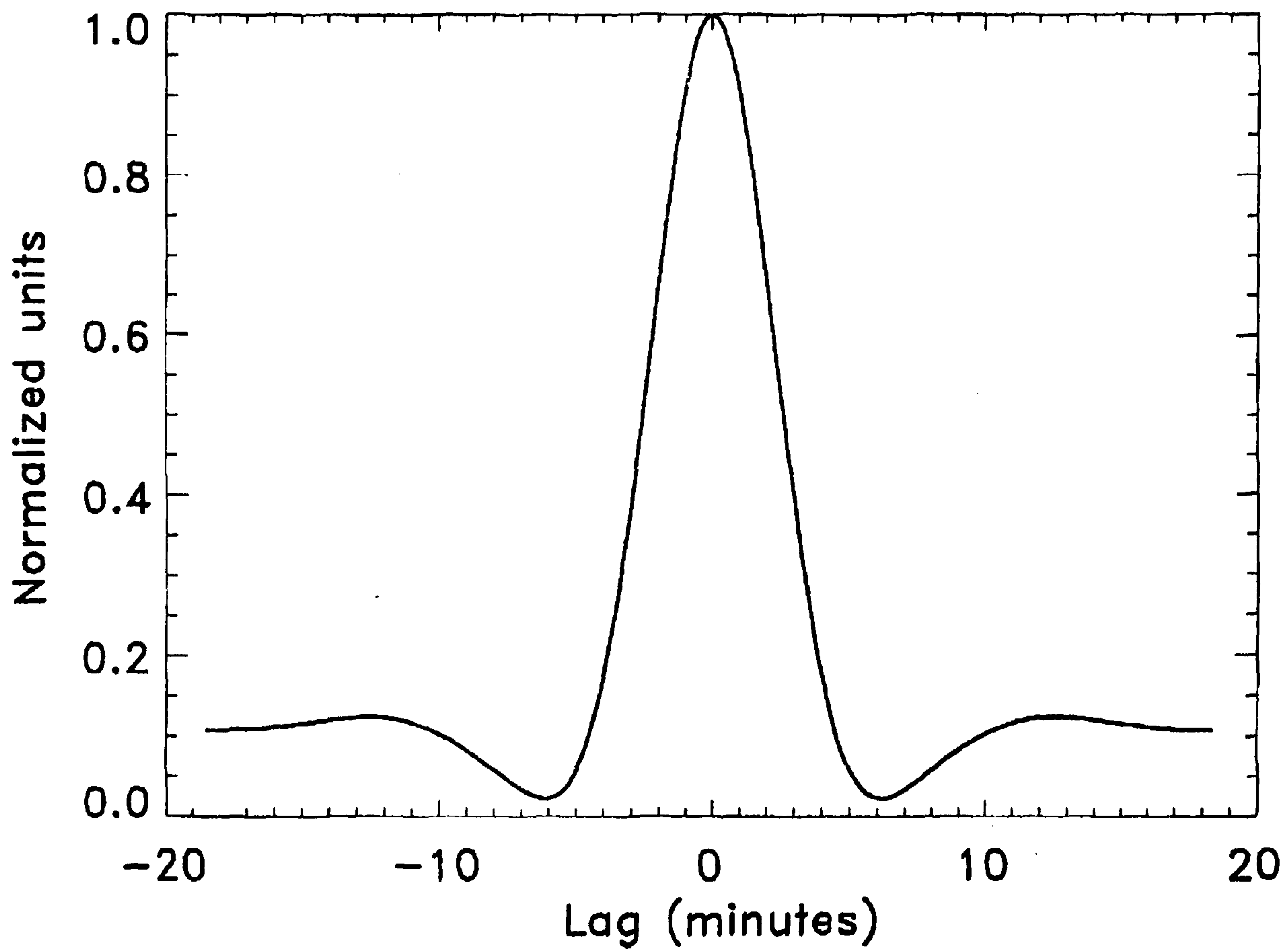

Fig. 2

Model

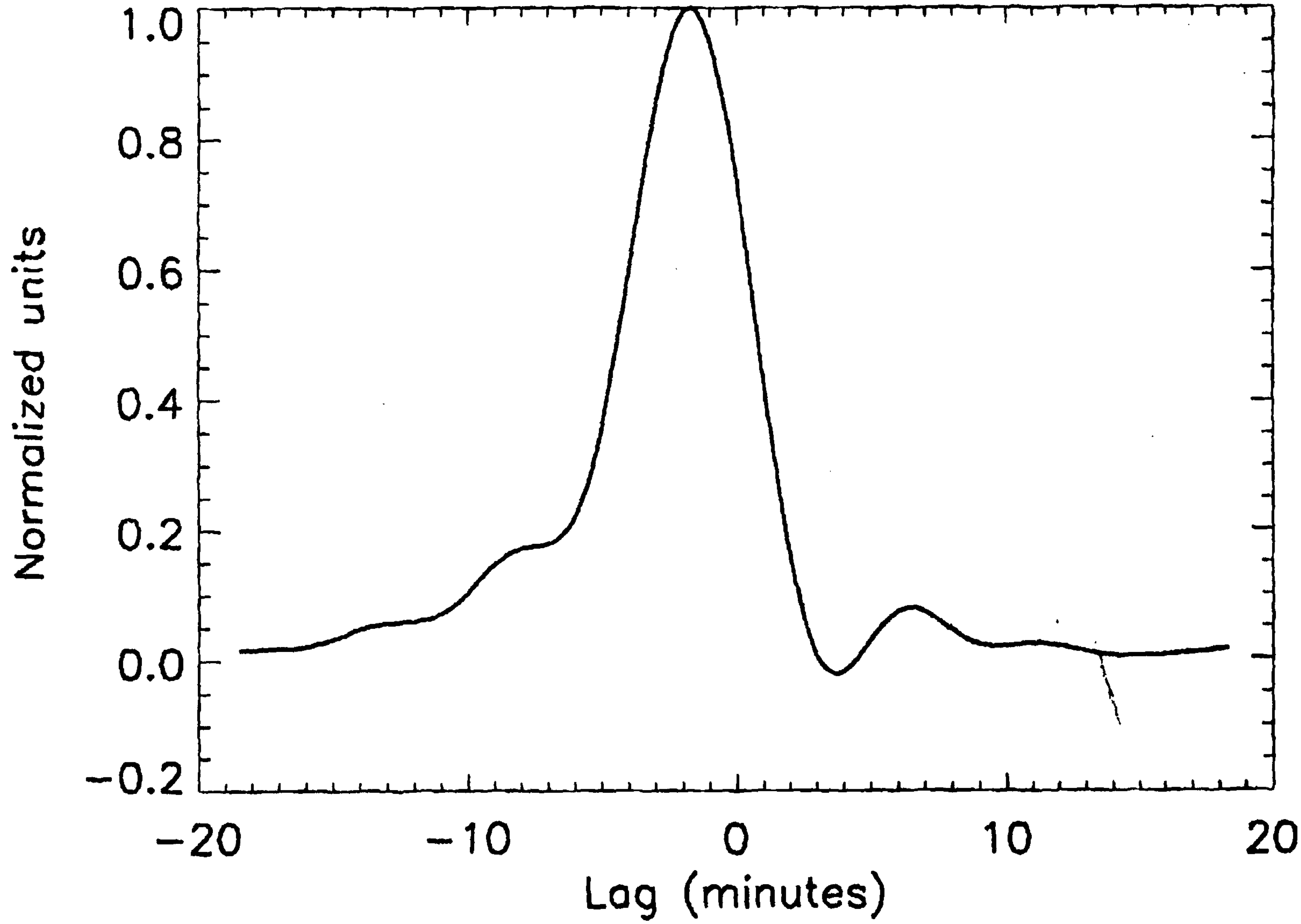

Fig. 1

Fig. 3